Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

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Lecture: 60

Characterisation of materials I

Hello everyone, I welcome you all to another class of biomedical ultrasound course and in today's class we will be talking about the characterization of materials, and I am Simranjit Singh, a NPDF fellow at IISC Bangalore. Coming to the very basic question, we will initially talk about why we need characterization and before even talking about why we need characterization, let us talk about materials. Now, let us come to the very generic question like what materials are. Now, if you look around yourself. the chair in which you are sitting or the table on which you are keeping your laptop or even in the screen that you are viewing me. So, everything is made up of some kind of material, and materials are made up of matter.

Now matter has a very generic definition. Anything that occupies space and have mass is called matter. Now, every matter in the universe is made up of molecules which are bonded together by some kind of bonds and because these bonds are unique to that material, so they will have a specific or generic properties or some characteristics like color, shape and sizes etc. So, let us talk about the very basic examples like coming to the very basic examples of properties of materials let us talk about.

So, supposing, we have this object. So, supposingly we have this pen. So, what is the first thing that you will see or about this pen. So, you will probably say that the first thing I will notice about the pen is about its color. So, the color that you are seeing is the pinkish red.

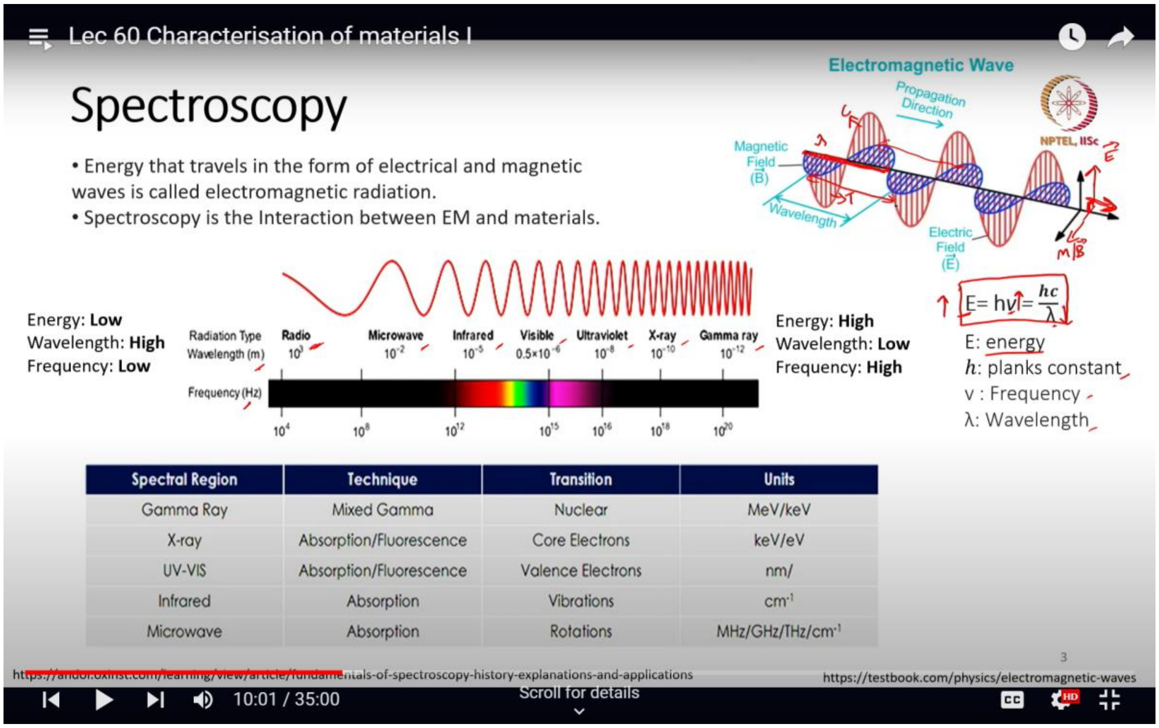
So, this is because it is reflecting the pink color, and it is absorbing all the other wavelengths. So, that we will say is its optical property. Now, talking about another property, let us talk about the thermal one. So, if I heat this pen from this end, it will eventually melt because it is made up of plastic, but I would not feel the heat in the other end because it is a bad conductor of heat. So, this we already know because of the property of plastic.

And supposedly if I replace this plastic pen with a metallic pen, so metallic pen if I heat from here, I will instantly feel the heat at the other end because metals are a good conductor of heat. And similarly, if we go to the electrical properties. So, if I make a circuit using a bulb and the battery and I place this pen in between them and I complete the circuit, I will see that the bulb will not glow because our pen which is made up of plastic is a bad conductor of electricity. And if I replace this with a metal or some other form of metal, I will see that it will conduct electricity because the metals that we have are a good conductor of electricity because these are the electrical properties of the plastic pen and the metal that I am talking about. Similarly, if I talk about some of the very basic generic mechanical property, so if I have to bend this pen, this pen will eventually break and if this is made up of metal. So, metal have a property that it can be drawn into wires. So, if I bend a metal, it will easily bend, but if I try to bend this pen it will eventually break. So, these are the properties of the metals and the plastic that I am talking about. Similarly, let us talk about some other properties.

If I have this pen and I have dipped it in water for around 30 minutes, 40 minutes or even a day, what do you think will happen? Yeah, nothing will happen to this pen because it is made of plastic. Now if I have a pinch of salt instead, if I put it in a glass of water, you will see that the salt will eventually dissolve. Now what is dissolution? Dissolution is it will eventually break into Na plus and Cl minus. So, it will dissolve. So, these are you can say the chemical properties of the salt and the pen I am talking about.

Now we have another property which is called the magnetic property. So, to understand this you can have a simple analogy. If you bring a magnet and you bring it very close to this pen, you are right that the pen will not attract to the magnet because this is not a magnetic in nature. Now supposingly if I have an iron pen, so iron pen will attract the magnet because of its properties. Now, the point that I am making is that all the materials have their specific properties and to measure these properties of the materials, the measuring of these properties of the material is called characterization.

So, we need a tool called characterization to measure all the different properties of the materials. Now in this lecture we will be specifically focusing on the optical properties. Now amongst all the mechanical, chemical, thermal, electrical and the optical properties in this lecture we will be talking about the optical properties and specifically in that we need something which is called spectroscopy. Now we will be studying spectroscopy in our next slide. So yes, so coming to the very basics now what is spectroscopy? Now before even talking about spectroscopy let us talk about very basics of EM waves.



Now EM waves are the energy that travels in the form of electrical and magnetic field in our universe. So, this is very elementary, you must have studied this in your primary class. maybe, but let us talk about this because we will be talking about the EM waves in detail and also, I will be repeating this the terms of EM waves. very frequently. So, it is important to learn about them.

So, let us talk about the EM wave. So, if this is the direction in which our electromagnetic wave is moving. So, we have the two components in EM waves. The first one is the electric field, and the other one is called the magnetic field which I will represent as M or you can also represent as B. So, these are the two components of the electromagnetic field, the electromagnetic waves and we see that they are perpendicular to each other, and they are also perpendicular to the direction of the motion of the EM wave.

So, these are the two components of electromagnetic waves and also, I will be talking about some of the basic terms. Let us talk about some of the basic terms like wavelength. So, our EM waves follow a sinusoidal pattern. So, we have something which is called crest, and we have something which is called trough. So, the above region is called crest, and the below region is called the trough and also the basic terms which is very frequently used are called wavelength, frequencies and energy. Energy is the energy of the wave by which it travels. The wavelength we talk about is the distance between two consecutive troughs or you can talk about two consecutive crest, or you can talk about this distance. So this distance here from one particular crest to one particular trough is called the wavelength and it is represented by lambda and also there is a term which is called frequency. Now frequency can be understood by the number of oscillations this electromagnetic wave is having in a particular second.

So, we have here a basic formula which is E is equal to h nu or we have a relation in which E is equal to hc by lambda. So here E is our energy of the EM waves. The mu here is the frequency and the lambda here is the wavelength of the EM waves and our h is our Planck's constant. So, there is a relation and according to it if we increase the energy. our frequency is directly proportional to frequency would also increase, but our wavelength is inversely proportional.

$$E = h\vartheta = \frac{hc}{\lambda}$$

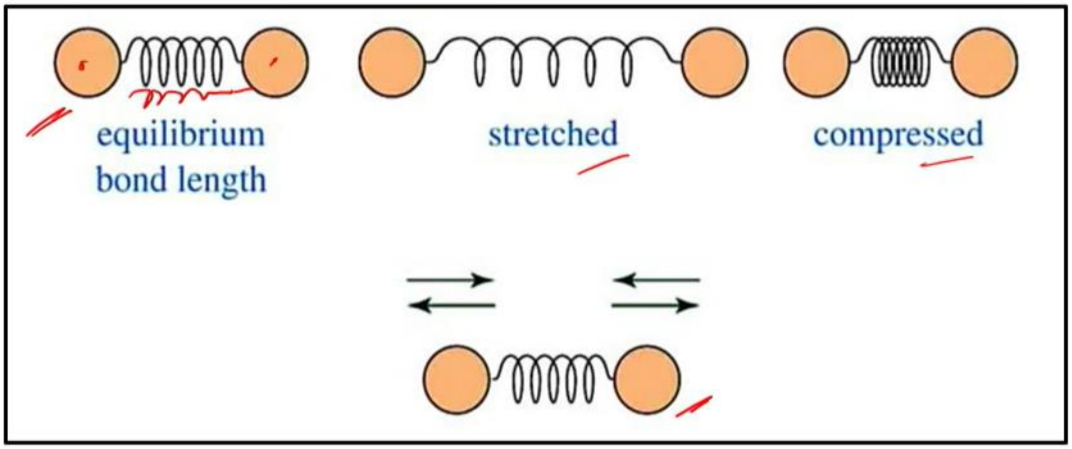
So, you are right the wavelength will decrease. So, based on the wavelength and the frequency we have divided the electromagnetic spectrum into various kinds of you can say about various kinds of waves depending on the wavelength and the frequency. So, we have something which is called radio waves, we have something which is called microwaves, we have the infrared waves, we have the visible region, we have the ultraviolet, we have the X-rays, and we have the gamma rays. So, these are all classified based on the wavelength and the frequency. So, let us first before moving to the technical part, let us first talk about the very basic applications of this waves.

You must have heard about some of these waves in your practical application. So, let us talk about the practical applicability of all the segments of the EM waves and how we are using it in our daily lives. So, we have the radio waves, so the radio waves we are extensively using these in our daily telecommunication networks. So these are usually used for the communication devices, we have the microwaves, so we all In today's world, we all have microwaves at home. So, we heat our food with the help of microwave.

So, microwaves we are using daily to heat our food and then we have infrared rays. So, infrared rays are used in our daily remotes. So, the remotes that we have for the electronic devices to change the channel or the AC remotes, TV remotes, any remotes that you have has the infrared sensor on top of that. and then we go to the visible region. This visible region is the only region of the electromagnetic spectrum that we could visually see and so this is the part of the electromagnetic spectrum.

It is called infrared. So, because it is just beyond the red region that is why it is called infrared here and we have the ultraviolet because it is just beyond the violet color. So, we call it ultraviolet. So, coming to the next we have the ultraviolet. So, ultraviolet is usually used for sterilization. So, it kills the bacteria in some form of sterilization processes in industries it is used.

So, it is one of the examples and then we have x-rays if you are lucky, you might not have faced x-rays, but whenever you face an accident or something you usually doctor prescribes x-rays to image your bones. So, x-rays are used for that and then we have gamma rays. So, gamma rays are very high energy in nature it is usually used in nuclear physics or for reactions and everything. So, what we see from here that when we go from the radio waves towards the gamma rays our energy is increases. So, from left to right the energy is increasing.



So, according to this relation you can pause the video and think about what will happen to the frequencies and the wavelength I am talking about. So, just refer to this relation and think whether if the energy is increasing from radio waves to gamma rays what will happen to the wavelengths or the frequency. So, yes you are probably right I have also written here. So, if the energy is low, so here for the radio waves the energy is low.

So, our wavelengths are high. So, here if we see the wavelength I am talking about lambda here. So, the wavelength here is larger and if you see wavelength of the gamma rays it is very less. So, the order I am talking about is the wavelength is about 10^3 meters and to the order of 10^{-12}. So, this much difference is there when we go from the radio to the gamma rays. And similarly, if you talk about the frequency, frequency is directly proportional. So, if energy is low our frequency is also low.

So, the frequency if you want to compare, so frequency is measured in Hertz. So, it is of the order of 10^4 for the radio waves. it moves up to the order of 10^{20} in case of gamma rays. So, this is all the basics of the EM waves and all the classification of those and after talking about the practical applicability let us talk about how we can utilize this in our characterization of materials. So, we have a table here in which I will draw first it will be much easier for you.

So, the energy is increasing from the microwaves to the gamma rays here. So, let us practically talk about all these waves and how we can use it for the characterization of materials. So, first we have the microwaves, microwaves are very low in energy as I already talked about. So, this can usually change the rotation of either the electrons or the nucleus. So, we can use it in electron magnetic resonance or ESR spectroscopy.

So, we can have an application in that. It gives us an idea about the rotation of electrons. Then we have the infrared rays, infrared rays are slightly more energetic than the microwaves. Now these infrared rays will be absorbed by the molecules present in your material and it will cause vibration. Now this absorption will be called vibration, and it will give us the characteristic information about what all bonds are present in that material. Moving towards the UV visible, UV visible is slightly higher in energy.

So, it will cause electronic transitions. So, we can measure the electronic transition in detail. I will discuss this in the next lecture. So, then we have the X-rays. X-rays we can use they are higher in energy. So, they can knock the innermost electrons of the atoms.

So, this can be used for X-ray diffraction and also X-ray fluorescence. So, this we will be talking about later. And, then we have the gamma rays. So, gamma rays are very highly energetic in nature. So, we usually do not use it in general characterization.

So, this is extensively used for nuclear reactions and nuclear physicists. The takeaway message is that if we talk about the characterization of materials, we extensively use these three regions of the electromagnetic spectrum where we have the X-rays, UV visible and the infrared rays. And in this lecture, we will be talking about the infrared rays and how we can use this and the practicable applicability of the IR rays for the characterization of materials. Okay, let us talk about the basics of the IR spectroscopy. Now to understand the IR spectroscopy you have to take an analogy in which you have two ping pong balls, and which is attached by a spring.

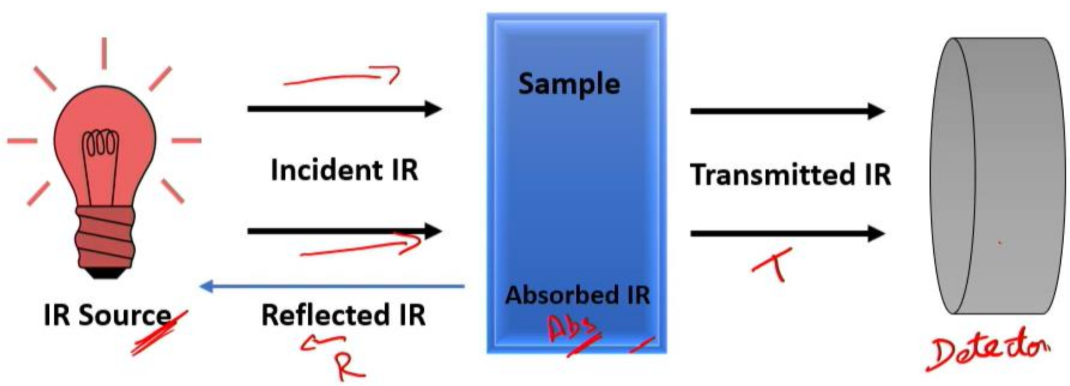
So here you see this figure. So here we have two ping pong balls, and this is attached by a spring. So, after it is attached by a spring you can imagine that if we compress or we stress that spring it will eventually vibrate. So, that is the basic, it can either be stressed or compressed and it will cause some kind of vibrations right. So, this is the analogy of the principle of IR spectroscopy. So, in which we say that every bond, every molecule is bonded by a spring kind of bond and every bond has a natural resonance frequency in which it vibrates.

So, every molecule has its particular vibration. So, depending on the type of bond and the type of molecule we can have different vibrations in a particular molecule. So, let us take some examples. So, here we have the different kind of vibrations that can be present in a molecule. So, it can be symmetric stretching. So, this can be possible symmetric stretching in which both these atoms are moving together.

We can have an anti-symmetric stretching in which these are moving anti parallel to each other. So, the motion is not together and then we can have rocking in which both of the bonds are moving towards the sides. We can have a wagging kind of bonds in which both the atoms are moving in front. So, in front of the screen if you can see and then we can have something which is called twisting. Twisting is a kind of anti-parallel stretch between the both the molecules in the plane which is coming right forward.

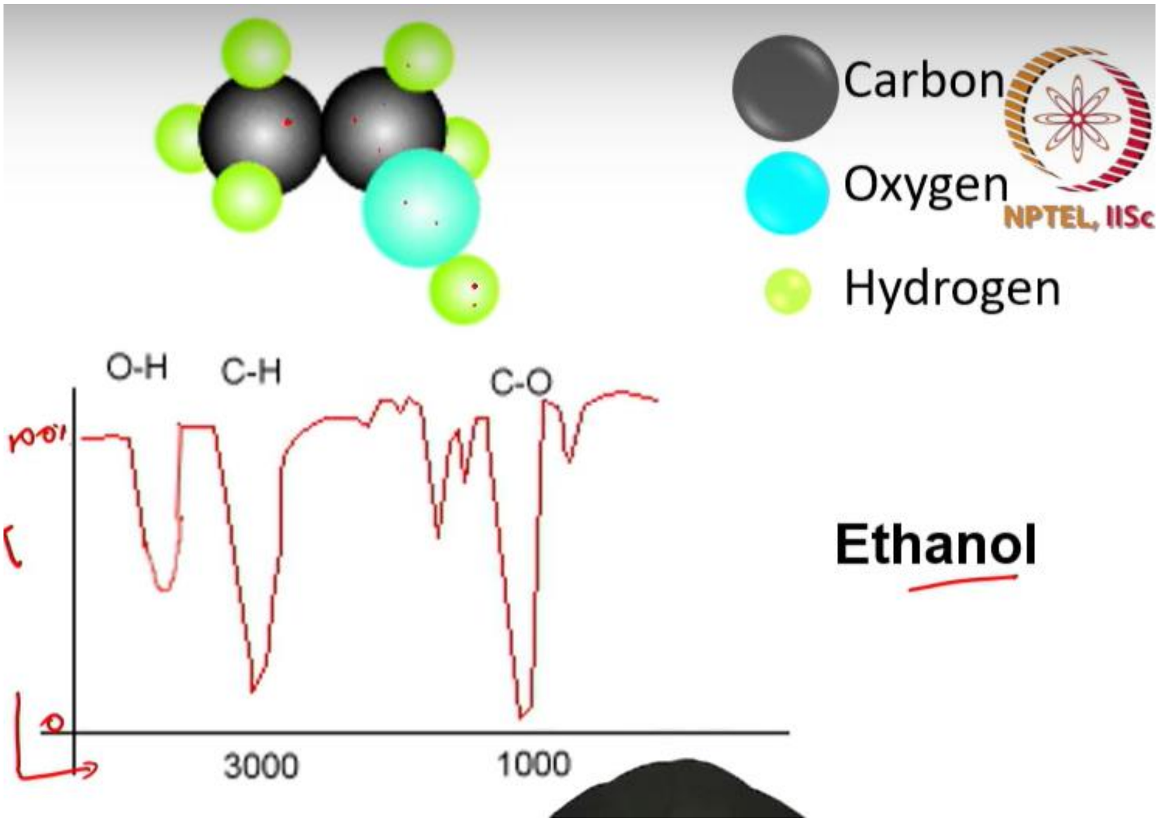
Then we can have scissoring. Scissoring can be anti parallel motion. in which both the molecules are moving in the sidewards direction or in the y direction you can say. So, these all kinds of vibrations can be possible in some molecules and based on that we have a technique called IR spectroscopy and it can detect what molecules are present depending on the type of vibration it shows. So, coming to the working mechanism.

So, let us first talk about the instrumentation. So, the necessity for the IR spectroscopy is the IR source. So, we have a IR source. We have a sample which is kept at a distance to from the IR source. So, it can absorb some of the IR and then here we have the detector right.



So, we have the IR source. So, IR source incident some of the IR light onto our sample. So, some of the parts are reflected back which I will represent as R. So, some of the IR rays would be reflected back to the source and here is our sample. Our sample will absorb some of the IR light and some of the IR light would also be transmitted. So, whatever light is not absorbed by the sample would be transmitted.

So, transmitted is the non-absorbed light from the sample. So, and then the transmitted light reaches our detector. what basically we say that this is the very basic plot of the IR spectrum that we get. So, we plot it in percentage transmittance versus the wave number here, so versus the wave number versus the percentage transmittance. So, the transmittance is 100 percent here on top and transmittance is 0 percent below. To understand this in detail, let us take an example of ethanol.



So, here we have the ethanol molecules. So, in which we have the carbon-carbon bonds, we have the carbon-oxygen bond, and we have the carbon-hydrogen bonds and we have the oxygen and hydrogen bonds. So, these all bonds are present in ethanol. So, based on the wavelength of the incident wavelength all of these bonds will absorb the specific wavelength and it will cause the natural which matches with the natural frequency, and it will vibrate. So, depending on the vibration we can record a spectrum, and we could get the characteristic IR spectrum.

For example, if we have OH. So, the transmittance will absorb start from 100 percent. So, whenever there is a OH vibration. So, we will get a characteristic OH peak then coming to the CH vibration we will get a CH peak for example, we have at 3000 then we have another peak here which is represented by CO it is around at the 1000 that you can say. So, depending on all every bond. it will absorb a specific wavelength of the IR and it will cause the natural vibration it will increase and we can finally see it in the IR spectrum.

Here. So, this is the characteristic IR spectra of ethanol and coming to one of the exceptions. So, if we talk about the IR we can actually identify what all bonds that are present in our material, but it has a limitation. So, in case we have polar bonds. So, supposedly we have carbon dioxide which is represented here. So, we have the carbon, we have the two oxygen bonds are there which are on the same plane and depending on that we could either have a symmetric stretch, we could have bent, we could have asymmetric stretch.

Now there is a concept that you must have probably studied in your plus 2 which is based on polarity. Now based on the electronegativity of every material like oxygen and carbon because they are different. So, because of the difference in electronegativity they can have a partial polarity, partial positive and partial negative which is delta positive and delta negative charges. So, as we have the vibration, we have the creation of delta positive and delta negative charge for some time and depending on that we have a polar bond and the non-polar bonds. So, what I was the point that I am trying to make is the polar bonds that we have is IR inactive.

So, supposedly if we have CO2, we have the asymmetric stretch and we have the symmetric stress. Now in the case of asymmetric one, we have a partial creation of polarity. So, this would be IR active, and it gives a bond at around 2, 3, 4, 9 centimeter inverse. which is the wave number while if we have the symmetric stretching like this it will be IR inactive. So, wherever we have the symmetric stretching or symmetric kind of vibrations that would be IR inactive while the asymmetric stretching or all the asymmetric vibrations would be IR active.

So, taking this into mind we get the IR spectrum, and we analyze it. We analyze the IR spectrum taking polarity into consideration. So, coming to the applicability part. So, we let us take one more example before that.

So, let us take a example of toluene here. So, we have a toluene. So, this is a structure of toluene, we have carbons and hydrogens, and we have the cyclic chain. So, you could see that it is plotted in percentage transmitted, and it starts from almost 100. So, you could see that there are several peaks representing several different kinds of bonds in toluene. So, we you could see that we have a peak around 3600.

So, 3060 I beg your pardon. So, that is for this CH stretching. And the peak at 2925 also represents the CH stretching and we have also CH stretching for at around 3033, but the aromatic and alkyl stretching are different. So, we can differentiate between them also. Our carbon and hydrogen show two different peaks. So, either they have as I talked about earlier it can either show stretching, or it can even show the bending kind of vibrations. So, we have both stretching peaks and bending peaks they are different we can differentiate them in case of carbon hydrogen C H bond.

And similarly, we have the C-C bonds and we have the C-H bending groups which is differently represented here. So, what I am trying to make that even if the carbon and hydrogen are same, we can distinguish between the aromatics or the alkyl C-H or we can differentiate between different types of vibration between them the C-H stretching or the C-H bending or these all kind of based on the vibration that are present. Now, let us talk about the applications. Now, the first application that comes to your mind is the identification of the unknown material. So, supposingly you have a unknown material like you are archaeologist and you get a unknown sample and you want to see what all material or what are bonds are present in case of that material.

Now the advantage of FTIR is that FTIR is non-destructive technique that means your sample is not being depleted in any kind of analysis. It is very easy to use you can directly use it and also it could be used in solid in thin films or even in liquid modes in some of the models of the IR spectroscopy. So, we can use it to find the identify the unknown bonds that are present in the materials. So, if you have the unknown sample archaeology sample and you simply run it through IR.

So, you will get an IR spectrum. So, something like this you will get and based then you match the all the peaks with the literature available. So, every bond will have the specific absorbance in the IR region and based on that we have a literature present. So, we have the standards literature which is present. So, we can actually match them with the standard and we can find out about what all unknown components are present inside our sample. And then another application that it can be used is so, supposingly a person is synthesis scientist.

So, supposedly he is a chemist, or he is a material scientist, and he has synthesized several kind of materials. So, supposingly he has synthesized ZNO I would talk about. So, supposingly he has synthesized these ZNO particles, and he want to see whether the material has been successfully synthesized or not. So, what he will do is that he will quickly run it through the FTIR and the FTIR will have the characteristic Zn and oxygen peak somewhere and that will eventually confirm whether our Zn and oxygen is present in this sample or not and he could say that after he sees there is a peak of Zn and oxygen he could say that my ZNO material has been successfully synthesized. Now, these are also used to study the chemical reactions and also in some cases whether some of the dyes or some of the materials has been absorbed on the surface or not.

So, supposedly we talk about an example in which ZNO is used for these ZNO particle that you have synthesized is used for some reactions in which there are some dye molecules or some drug molecules. that are eventually attached on the surface. So, you have the ZNO molecule and there are some drug molecules that I am saying. So, these are attached on top of that. So, we do a functionalization reaction, and we attach the drug molecules on top of the zinc oxide particles.

So, we want to see whether our drug molecule has been successfully attached to our surface or not to know that we will run it through IR. So, we will have the FTIR or the IR spectroscopy of ZNO alone, then we will have the drug alone. So, what we see the IR spectroscopy of ZNO and drug together. So, drug will have some of its characteristic peak or ZNO will have the characteristic peak and if all those peaks are present in our sample in which ZNO and drug are attached we could successfully say that our drug has been attached on to the surface. So, this could be extensively used for the biomedical field and also by the chemistry scientist, the chemical people, the archaeology people and also this confirmation of the drug molecule or any other molecule on the surface could be done by the help of the IR spectroscopy. Also coming to the electronic applications, so you have your MEMS devices, which has several steps of the metal deposition or deposition steps in which you deposit either the thin films or you clean the surface regularly. So, you can use the first very basically you can use it to identify the impurities in your samples. So, supposingly you have a silica wafer, and you do an RCA cleaning. So, you quickly run it through the FTIR or the IR spectroscopy to see whether our impurities all the impurities have been removed or not. And if IR detects any peaks that means apart from silicon if it detects any other peak that means some of the impurities are present on the samples and more cleaning is required.

So, detection of impurities can be done for the electronic devices and after every stage of the thin film deposition or in which we have multiple layer growth in which we deposit different thin films different metal deposition is taking place. So, after every step we can run it through the FTIR and we could see whether our metal has been deposited or if we are depositing some other oxide layer or some any other layer whether successfully being deposited or not, we can analyze using the FTI spectroscopy. So, it can be extensively used for the MEMS device or device fabrication also to analyze each step. So, after talking about the application I will summarize what we talked about today.

So, in summary we basically talked about the basic properties of materials. So, what are the basic properties of material like the optical, magnetic, the thermal and all the different properties we studied in very basic details and with then we talked about why we need characterization and why it is so important. Then, we talked about basics of the electromagnetic waves and their divisions, or the different electromagnetic waves based on their different wavelengths and the frequencies that are present. Also, we talked about some of the practical applicability where we are using these EM waves in our day to day lives and also how they can be used for the characterization Then, we talked about the spectroscopy and the basics of the IR spectroscopy and how the basic working principle of that, some of the basic instrumentation paths and then we saw the working mechanism and also we talked about some of the example of ethanol and the toluene and the carbon dioxide how some of the vibrations are IR active and some of the vibrations are IR inactive. So, we talked about that also then we talked about the practical applicability of the IR spectroscopy in the biomedical field in the archaeology field and also in terms of the material and the chemistry.

And also, finally we talked about how we can use it in the electronics device fabrication also. So, our FTIR in summary is very useful technique. It is non-destructive and you could use it extensively for various kinds of applications. So, that is all for today. Thank you very much and we will be talking about the UV visible spectroscopy in our next class.

Thank you very much.